Starburst Galaxies: Why the Calzetti Dust Extinction Law?

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ABSTRACT

The empirical reddening function for starburst galaxies generated by Calzetti and her co-workers has proven very successful, and is now used widely in the observational literature. Despite its success, however, the physical basis for this extinction law, or more correctly, attenuation law remains weak. Here we provide a physical explanation for the Calzetti Law based on a turbulent interstellar medium. In essence, this provides a log-normal distribution of column densities, giving a wide range of column densities in the dusty foreground screen. Therefore, extended sources such as starburst regions or HII regions seen through it suffer a point-to-point stochastic extinction and reddening. Regions of high column densities are "black" in the UV, but translucent in the IR, which leads to a flatter extinction law, and a larger value of the total to selective extinction, R_V. We fit the Calzetti Law, and infer that the variance σ of the log-normal distribution lies in the range $0.6 \leq \sigma \leq 2.2$. The absolute to selective extinction R_V is found to be in the range 4.3 to 5.2 consistent with $R_V = 4.05 \pm 0.80$ of the Calzetti Law.

Subject headings: galaxies: starburst — ISM: general — dust, extinction

1. Introduction

As Calzetti (2001) has made clear, the *extinction* curve of a single star by foreground dust should be distinguished from the *attenuation* curve of an extended object such as starburst galaxy or an H II region seen through a foreground dusty medium. The extinction for a single star depends simply on the column density and is determined by both the absorption and the scattering properties of the grains in the foreground dusty screen, since $\kappa_{\rm ext} = \kappa_{\rm abs} + \kappa_{\rm ext}$. In the case of an extended object the emitted light suffers an effective attenuation which depends strongly on the relative distribution of dust and emitting stars. In addition some of the measured flux can originate from light scattered into the observed direction. For all

these reasons, the effective attenuation will tend to be less than extinction we might expect from a simple foreground screen, and the intrinsic wavelength dependence of the attenuation might be expected to differ from the extinction curve of a single star.

From an observational viewpoint, an accurate knowledge of the appropriate attenuation curve for star-forming galaxies fundamental in helping us to understand the formation and evolution of galaxies. Very extensive use has been made of the Madau Plot (Madau 1995), in which the estimated star formation rate per unit co-moving volume of the Universe is plotted against red-shift. For high redshift galaxies, one of the principal means of populating this diagram is through a measure of the UV continuum, which should scale as the star formation rate (SFR) in galaxies with high specific star formation rates. However, these measures depend critically upon the dust attenuation corrections. These are very uncertain; there are claims that a typical $z = 3$ galaxy suffers a factor of ten extinction at 1500Å in the rest–frame of the galaxy (Meurer, Heckman & Calzetti 1999; Sawaki & Yee 1998). Others suggest more modest corrections (e.g. Trager et al. 1997). In normal disk galaxies, Bell & Kennicutt (2001) find that although mean extinctions are modest, about 1.4 mag at 1550Å, the scatter from galaxy to galaxy is large. For nearby starburst galaxies attenuation and SFR are strongly correlated Buat et al. (1999), and such a correlation extends to high-redshift galaxies (Adelberger & Steidel 2000). It is possible that many fainter galaxies at high redshift are completely missed, resulting in large uncertainties in the derived star formation rates.

Calzetti and her co-workers have been able to derive empirical attenuation curves across the full near-IR to far-UV spectral range. These have been given as local (piecewise) power-law fits of the form (Calzetti 1997, 2000, 2001; Leitherer et al. 2002):

$$k(\lambda) = \mathrm{A}(\lambda)/\mathrm{E(B-V)}_* = a + b/\lambda + c/\lambda^2 + d/\lambda^3, \qquad (1)$$

where a, b, c, and d are constants in a given wavelength range and $\mathrm{A}(\lambda)$ is the attenuation in magnitudes at wavelength λ, $\mathrm{E(B-V)}_*$ the color excess of the stellar continuum light. The total to selective attenuation of the stellar continuum, $R_\mathrm{V} = \mathrm{A(V)}/\mathrm{E(B-V)}_* = 4.05 \pm 0.8$. Experimentally, Calzetti (1994) showed that the HII regions are more heavily attenuated than the stellar continuum, presumably because these are associated with more dusty regions of ongoing star formation. Although, from galaxy to galaxy, there are considerable variations from the Calzetti Law it has nonetheless proved to be very useful and is widely used by observers.

The purpose of this paper is to remove some of the empirical aspects of this fit, by deriving an analytic fit to the attenuation based on a turbulent model of the interstellar medium, and using the interstellar grain model of Weingartner & Draine (2001). We show that, within a certain range of parameters, and neglecting environmentally-dependent dust properties, the theoretical attenuation of a turbulent dust screen agrees well with the Calzetti

law. We also provide an estimate of how this attenuation law might change as we observe starburst galaxies with a larger global attenuation, such as are found in the high-redshift universe at the epoch of galaxy formation.

2. The Extinction of a Turbulent Foreground Screen

2.1. Density Fluctuations

The interstellar medium (ISM) cannot be considered as homogeneous in any galaxy. The phase of the ISM which influences the attenuation law is not primarily the gravity-dominated molecular clouds or Bok Globules, which are highly optically thick, but rather the more diffuse turbulent phase. Calzetti (1996) and Calzetti (1997) have investigated the effect that a two-phase clumpy medium would have on the attenuation law. This model has clumps of identical optical thickness providing a certain covering factor in the foreground dusty screen. The result of this is generate a stochastic reddening which results in a flatter attenuation law than the standard interstellar extinction law.

This simple model shows how inhomogeneities in the ISM can provide a qualitative explanation of why the Calzetti Law works. However, it is very simplistic. We now understand that the inhomogeneities in the non-gravity dominated phases of the ISM are likely to be the result of turbulence. In the diffuse phases, MHD turbulence may apply, with the magnetic field being an important contributor to the total pressure. MHD turbulence can provide a natural explanation for the famous FIR:radio correlation in galaxies (Groves et al. 2002).

All turbulence is characterised by a wide range of densities. As shown by simulations of compressible hydrodynamic turbulence the density distribution is well described by a log-normal distribution if the turbulence is approximately isothermal (see Ostriker, Stone & Gammie (2001) and references therein) where the log-normal distribution is given by:

$$\begin{aligned} p(\ln(\rho)) &= \frac{\mathrm{d}p(\ln(\rho))}{\mathrm{d}\ln(\rho)} = \frac{1}{\sqrt{2\pi}\sigma} e^{-x^2/2\sigma^2} \\ \text{with} \quad x &= \ln(\rho) - \ln(\rho_0). \end{aligned} \tag{2}$$

Here, the mean $\langle\rho\rangle = \int \mathrm{d}(\ln(\rho))\,\rho\, p(\ln(\rho)) = \rho_0\, e^{\sigma^2/2}$. Nordlund & Padoan (1999) have shown analytically that the density distribution in supersonic and isothermal turbulence is a log-normal distribution. In principle the distribution becomes wider with increasing Mach number M. In particular, for unmagnetised forced turbulence Nordlund & Padoan (1999) and Padoan, Jones & Nordlund (1997) found that the variance is correlated to the Mach number by:

$$\sigma^2 = \ln\left(1 + \beta^2 M^2\right) \tag{3}$$

with $\beta \approx 0.5$. However, in general, no simple dependence between Mach number and density contrast has been found (Ostriker, Stone & Gammie 2001).

As discussed by Ostriker, Stone & Gammie (2001) the distribution of column densities $N = \int \mathrm{d}l\, \rho(\vec{r})$ for an isothermal turbulent medium is also approximated by a log-normal distribution. Thus, in a turbulent medium, as long as the dust size distribution and composition (which determines the absorption coefficient, κ_λ, at wavelength λ) is not a strong function of density, then a log-normal distribution should also characterise the effective optical depth, $\tau_\lambda = \int \mathrm{d}l\, \rho(\vec{r})\, \kappa_\lambda = \kappa_\lambda N$. When the correlation length of the turbulence is much less than the scale thickness of the absorbing layer, the contrast in column density will be smaller than the density contrast (Ostriker, Stone & Gammie 2001). Thus, if equation (3) is valid, the contrast in column density can be used to obtain a *lower* limit of the Mach number.

2.2. Dust and Attenuation Model

We have adopted the Weingartner & Draine (2001) dust model with Galactic abundances and $R_\mathrm{V} = 3.1$ as providing the (currently) most sophisticated theoretical fit to the local extinction curve. In the more extreme UV radiation fields encountered in starburst galaxies, this grain model may not be an appropriate choice, because the small carbonaceous grains containing large amounts of PAHs are likely to be destroyed. The main effect of this will be to suppress the 2200Å feature, which in starburst galaxies is either very weak or absent.

To account for extinction it is important to know the relative distribution of stars and gas. Since the foreground dust screen model has proved to be most successful in describing the attenuation properties of galaxies (Calzetti 2001), here we assume that the attenuation is caused by a turbulent screen in front of the emitting stars. Other geometries will be investigated in a later paper. Because of the distribution of column densities in this screen the star light suffers, either by absorption or either by scattering at dust grains, a range of attenuation $e^{-\tau}$. The ratio of the observed to the emitted light of all stars can be attributed to an effective optical depth τ_eff. Its value is given by the averaged attenuation:

$$\begin{aligned} \tau_\mathrm{eff} &= -\ln\left(\int \mathrm{d}\ln(\xi)\, p(\ln(\xi))\, e^{-\xi\langle\tau\rangle}\right) \\ &= -\ln\left(\int \mathrm{d}y\, p(y)\, e^{-e^{y}\langle\tau\rangle}\right), \end{aligned} \tag{4}$$

where $p(x)$ is the log-normal distribution of $\tau/\langle\tau\rangle = \xi = e^y$ and $\langle\tau\rangle$ the averaged optical thickness of the screen.

3. A Fit to the Calzetti curve

The analytical form of the Calzetti attenuation curve given by equation (1) is itself a fit derived from a large number of observations made in different wavebands. To model this extinction curve, and to obtain some idea of the uncertainties in both the data and our fitted model, we need to fit to data points from which the Cazetti curve is derived. This proved to be rather difficult, because the errors are not very well constrained in much of the fitting procedures used by Calzetti. We have adopted the following compromise. In the range of 0.25 to 1.65 μm we have used two data sets given in Calzetti (1997). These give the selective obscuration at seven wavelengths, $E(\lambda - 2.2\,\mu\mathrm{m})_*/E(B-V)_{\mathrm{HII}}$ derived from the $\mathrm{E(B-V)}_{\mathrm{H}_\alpha/\mathrm{H}_\beta}$ and the $\mathrm{E(B-V)}_{\mathrm{H}_\beta/\mathrm{Br}_\gamma}$ correlations. First we combined both data sets (f_1, f_2) with their respective uncertainties σ_1 and σ_2 by taking an weighted average: $\langle f \rangle = (f_1/\sigma_1^2 + f_2/\sigma_2^2)\,/(1/\sigma_1^2 + 1/\sigma_2^2)$. After applying their recommended correction to the stellar selective extinction, $\mathrm{E(B-V)}_* = 0.44\,\mathrm{E(B-V)}_{\mathrm{HII}}$, we found that almost all these data points lie well above the values of the selective obscuration obtained from the analytic formula (1). To allow a comparison of the model with the Calzetti curve we scaled the data by a factor 0.785 which minimized the χ^2 of the data values in the range from 0.26 to 1.65 μm with respect to the analytical curve. The derived values are summarised in table 1. With the exception of the measurement at 0.16 μm these values are in excellent agreement with the analytical curve of fig (1).

To extend the fitting region to wavelengths shorter than 0.16 μm we have added two further points at 0.125 and 0.105 μm based on the HUT measurements of the selective obscuration $\mathrm{E}(\lambda - 0.15\ \mu\mathrm{m})/\mathrm{E(B-V)}_*$ given by Leitherer et al. (2002). The absolute values were found by normalising to the point at 0.16 μm. As a consequence of this normalisation, these points lie below the $k(\lambda)$ of the Calzetti curve. This difference illustrates how sensitive the curve is to errors in the piecewise fitting procedure. We will refer to the $k(\lambda)$ values given in table (1) as $k'(\lambda_i)$.

Table 1: The data points used to fit the extinction curve of star-burst galaxies. Here, $k'(\lambda) = \mathrm{A'}_\lambda/\mathrm{E(B-V)}_*$ and $\Delta k'(\lambda) = \Delta\,\mathrm{A'}_\lambda/\mathrm{E(B-V)}_*$.

λ [μm]	0.105[1]	0.125	0.16[2]	0.26	0.44	0.55	0.70	1.25	1.65
$k'(\lambda)$	11.71	10.02	8.37	7.59	5.07	4.08	3.15	1.28	0.70
$\Delta k'(\lambda)$	1.59	0.77	0.49	0.81	0.46	0.38	0.38	0.15	0.16

[1]Based on Leitherer et al. (2002)

[2]Based on Calzetti (1997)

In our fitting procedure, we used the theoretical turbulent cloud structure discussed in the previous section, described by a mean extinction $\langle A_V \rangle = 2.5 \langle \tau_V \rangle \log(e)$ and variance $\sigma_{\ln(\tau/\langle\tau\rangle)}$ of the log-normal distribution of the optical thickness τ. These theoretical parameters together determine a unique attenuation curve which we derived using the dust model of Weingartner & Draine (2001). In practice, we find that all attenuation curves having the same effective value of the total to selective extinction, R_V, are almost identical, and that each value of R_V can be represented as a curve on the $\langle A_V \rangle : \sigma_{\ln(A_V/\langle A_V \rangle}$ plane. Likewise, lines of constant effective attenuation of the screen, A_V, can also be represented by curves on this plane *s*ee fig (2)). Note that for small values of σ, the effective attenuation is the same as the mean extinction, as it should be for an (almost) uniform medium.

To determine the parameters required to fit the Calzetti curve, we fitted the obscuration $k'(\lambda_i)$ using a χ^2-fit. To avoid the uncertainties in the absolute value in the analytical formula which had been measured independently in respect to the selective obscuration (Calzetti 2001), we retain an additive constant as an additional free parameter.

The result of the χ^2-fit is shown as contours in figure (2). The best fit has reduced χ^2 of 0.048. This is an excellent fit and suggests the data errors may have been overestimated. The corresponding attenuation curve is shown in figure (1). Below a variance of $\sigma_{\ln(\tau/\langle\tau\rangle)} \approx 2$ the range of solutions inside a certain confidence level is consistent with a restricted range of R_V. The solutions of 68% confidence constrain R_V in the range $4.3 \leq R_V \leq 5.2$. This is consistent with the value given for the analytical extinction curve ($R_V = 4.05 \pm 0.8$).

The range of physical solutions are further constrained by the absolute attenuation characterising the observed galaxies; $0.25 < A_B < 2.78$ with a mean of 0.78, or $0.20 < A_V < 2.23$ (Calzetti 2001). From figure (2), these values, combined with the limits derived above on R_V restrict σ to lie in the range $0.6 - 2.2$ with a most probable value $\sigma \sim 1.0$.

Through the IR to near-UV, the quality of our theoretical fit to the Calzetti curve is remarkable. In the UV, the obvious deficiency is the inclusion of the 2200Å absorption feature, which reflects the deficiencies in our simple grain model, which does not take account of the destruction of small carbonaceous grains in starburst environments.

4. Discussion & Conclusions

We have demonstrated that the theoretical attenuation of light through a turbulent dusty foreground medium can provide an excellent fit to the empirical Calzetti attenuation curve, provided that $0.6 < \sigma_{\ln(A_V/\langle A_V \rangle} < 2.2$ and $4.3 \leq R_V \leq 5.2$. If formula (3) is correct, the inferred contrast in column densities implies a *minimum* value of the Mach number in

the dusty layers in the range of 1.3 to 22.

These numbers can be compared with estimates appropriate to the warm neutral medium (WNM) and the cold neutral medium (CNM) of galaxies. When the vertical velocity dispersion of quiescent disk galaxies is measured it is found to be remarkably constant. The H I observations, which are sensitive to the WNM, give vertical velocity dispersions between 7 and 10 km s^{-1} (van der Kruit & Shostak 1982; Shostak & van der Kruit 1984; Kim et al. 1999; Sellwood & Balbus 1999). The 3D velocity dispersion will be $\sqrt{3}$ times these values. Assuming that the WNM has a temperature of order 6000K, this implies $M \sim 1.8$ in this component. For the warm ionised medium (WIM), the estimated Mach number is very similar. For the CNM, we can use estimates based on observations of CO, which give vertical velocity dispersions of $6 - 8$ km s^{-1} (Combes & Becquaert 1997). Assuming a temperature $\sim$ 100K in this component, we have $M \sim 12$. Starburst galaxies are characterised by somewhat higher velocity dispersions so we would expect that for these the Mach numbers are somewhat higher. Nonetheless, the agreement of these estimates with the numbers provided by the dust attenuation law fit is very pleasing, and gives greater confidence that the ISM density structure in the dusty ISM is determined by turbulent processes acting in the relevant phases.

It is somehow surprising that the attenuation model works so well even without the inclusion of scattered light. This is in contradiction to expectation that the losses due to scattering cancel - every photon scattered out of the viewing direction being compensated by another photon scattered into this direction. However, it is easy to understand that the out-scattered photons cannot be totally compensated by the in-scattered photons because the distance the scattered photons travel through the dust screen is different and the total optical depth experienced by the photons which are scattered into the viewing direction is always larger.

A further reason why the scattering does not contribute significantly to the attenuation may be caused by the clumpiness of the screen itself. It is true that the absolute contribution of the scattered light to the total transmitted light increases if the medium becomes clumpy. However, in comparison with the directly transmitted light this is a negligible contribution. Due to the log-normal distribution, the optical depth is mostly much smaller than the average optical thickness. It is in the high-density clouds where most of the extinction and scattering extinction occurs. The column density in such clouds is so high that photons, if they are not absorbed immediately, will suffer multiple scattering events until they are finally absorbed. Only photons scattered at the outskirts of these dense regions may escape and a small fraction will be scattered into the viewing direction. This will result in a slightly smaller extinction than that derived here.

To the extent that the turbulent ISM structure is invariant from one starburst galaxy to another, these models predict a correlation between R_V and A_V provided that the contrast in the column density is the same. As we go to a higher mean column density, the contrast in column density will decrease, as long as the local density contrast and the mean density remains constant. In a forthcoming paper, we show that a higher column density leads to a further flattening of the extinction curve and to an increase of R_V, mild in comparison to the increase in $\langle A_V \rangle$. This flattening in the reddening curve would be much stronger in more dusty galaxies or in violent systems with high Mach numbers, such as merging or collapsing galaxies. Thus we would expect that high redshift galaxies with strong star formation will have both large R_V and A_V. This remains to be confirmed by observation.

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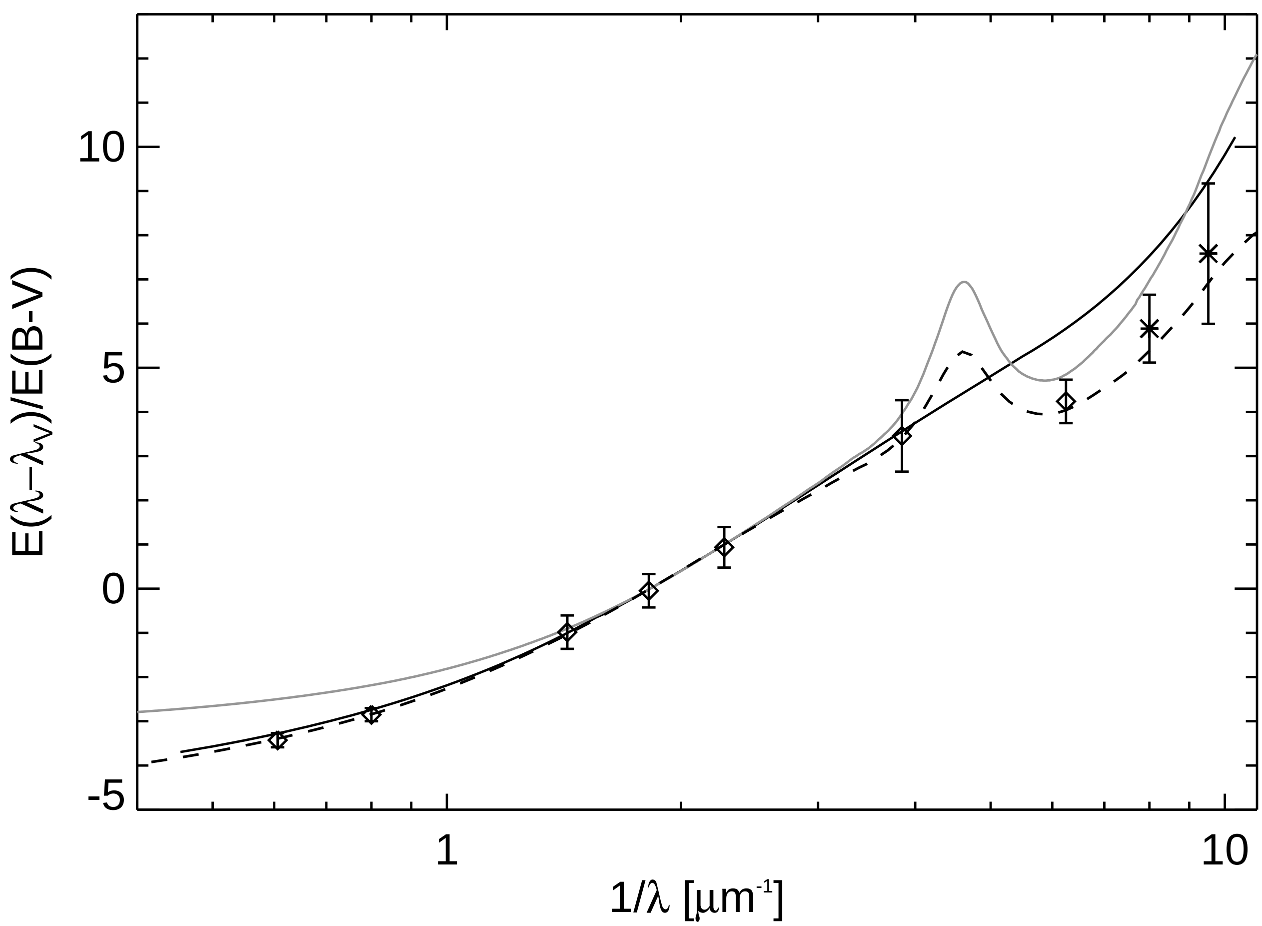

Fig. 1.— The theoretical fit to the Calzetti attenuation curve. The Calzetti curve itself is the dark solid line, and the data points used in the fit from Table(1) are shown along with their errors. The grey curve is the mean Milky Way extinction curve, and our least-squares fit to a turbulent foreground dust screen is shown as a dashed line.

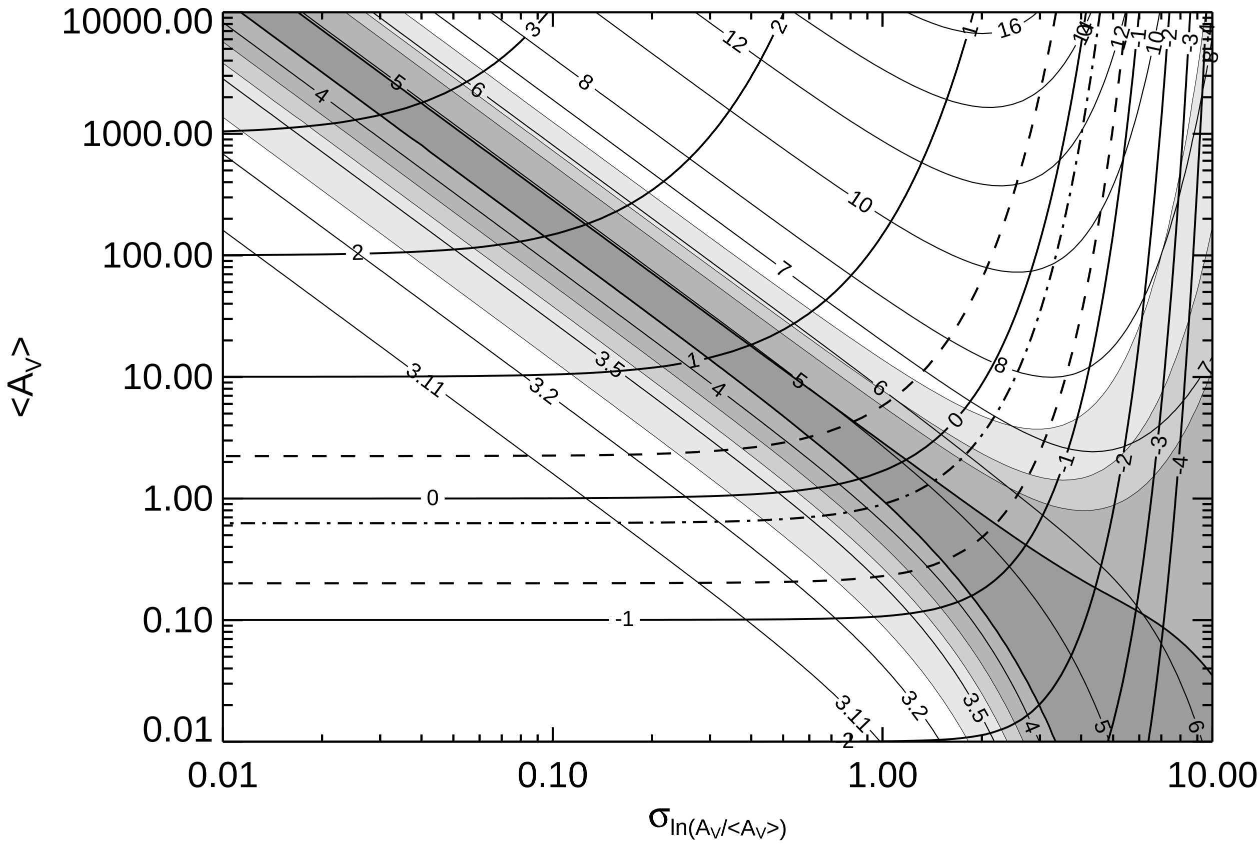

Fig. 2.— The observable quantities $\mathrm{A_V}$ and $\mathrm{R_V}$ are here plotted as functions of the theoretical parameters of the foreground screen, $\langle \mathrm{A_V} \rangle$ and the variance σ of the log-normal distribution of the optical depths $\tau/\langle\tau\rangle = \mathrm{A_V}/\langle \mathrm{A_V}\rangle$. The shaded contours represent the fitting to the Calzetti curve. The contours are the 68, 90, 95 and 99% confidence levels. The dashed, dashed dotted and dashed line are the lower, mean, and upper values of the attenuation observed in the galaxies. These are used to define the appropriate σ values which characterize the variation of column densities of the dust screen.